EUROPSIS
The European Program on Science and International Security

The Effects of Nuclear Terrorism: Fizzles

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This work is dedicated to the memory of the innocent souls that were lost in the 11/9 terrorist attack against America. Greece is mourning and praying for them. Next time the scientific community will be prepared.

Introduction

The **September 11** terrorist attack against America has caused a lot of concern to the American public and the entire world, which is suspecting a new attack sooner or later. The most frightening scenario is the one involving the detonation of a nuclear device at the heart of a large metropolitan city. Unless the terrorists are in possession of a fully assembled modern nuclear weapons it is very likely that they will possess a crude nuclear device which has been assembled in a terrorist camp by people with relatively limited technological resources. It well known that the Oppenheimer team which designed and tested the first nuclear weapon (the gadget) had a lot of reservations as to whether the first test at Alamogordo would produce any yield at all. This is due to the fact that in order to achieve a nuclear explosion (either using Uranium or Plutonium) very sophisticated knowledge is needed regarding fissile material geometry, detonation timing, shielding etc.

Therefore, the most likely scenario is that the terrorists will achieve either a nominal yield or no yield at all. As the effects of a successful nuclear explosion have been studied by various authors[1], we will only focus on the effects of an unsuccessful terrorist nuclear detonation known as "a fizzle ". That fizzle [2] can either be a complete nuclear failure where the chemical explosives of the device will simply disperse all the radiological material in the vicinity of ground zero (GZ) or it can involve the fissioning of some of the material which will amount to an explosive energy of some metric tones of TNT. In the study that follows we will investigate all those parameters that play a decisive role in the number of casualties after such an attack so that we can propose effective means of avoiding mass destruction.

This study relies heavily on complex mathematical modeling[3] of weapons effects but we will avoid using mathematical formulas in order to provoke

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[1] See for example "Arsenal, Understanding Weapons in the Nuclear Age" by Kosta Tsipis. Simon & Schuster publishing, New York, 1983, ISBN 0-671-44073-X

[2] Accidental fizzles in nuclear bases have already been studied by S.Fetter and F. Von Hippel (Science and Global Security, Vol.2 , No.1 (1990). In that study a large-scale model was used (wedge model) in order to predict the ensuing casualties of such an accident. In the present paper we will give detailed information about the radiological geometry and lethality of an intentional fizzle at short distanced from ground zero where the wedge model is not reliable. Besides the wedge model breaks down for extremely fine aerosols with deposition velocities close to zero.

[3] The present study relies on the code HOTSPOT 2.01 developed at LLNL by S.Homman. The code is based on the well-established Gaussian plume model, widely used for initial emergency assessment or safety-analysis planning.

interdisciplinary interest. Instead, we will present the results in a qualitative way so that the non-specialist can fully understand all the aspects of a terrorist nuclear attack. However, we have used a lot of footnotes in order to help the reader clarify certain technical points[4].

One might be deceived into believing that such an analysis should be classified so that no terrorist could exploit it. Such concerns are groundless as all the information used is carefully referenced and originates from the open literature. Besides, we will include a lot of technical footnotes, which can illuminate the physics package used in studying the attacks.

To study the attack in detail we need to define the parameters associated with it. The parameters of the attack are as follows:

1) Weapon model

a) Fission weapons

It is alarmingly well known by know that fission[5] nuclear weapons are of two types[6]. The first type uses Weapon Grade Plutonium (WgPu) while the second uses Weapon Grade Uranium (WgU). The isotopic composition[7] of WgPu is: plutonium-

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[4] To clarify certain technical parts of this paper a few of its footnotes where taken from Carey Sublette's excellent work NWFAQ (now mirrored at the site of the Federation of American Scientists: FAS). The author of the present paper has adopted only those parts of the NWFAQ whose physics is obvious and well cited. Some parts are adopted verbatim while others have been carefully screened and modified appropriately.

[5] Nuclear fission occurs when the nuclei of certain isotopes of very heavy elements, isotopes of uranium and plutonium for example, capture neutrons. The nuclei of these isotopes are just barely stable and the addition of a small amount of energy to one by an outside neutron will cause it to promptly split into two roughly equal pieces, with the release of a great deal of energy and several new neutrons. If on average one neutron from each fission is captured and successfully produces fission then a self-sustaining chain reaction is produced. In such case the fissionable material is called CRITICAL. If on average more than one neutron from each fission triggers another fission, then the number of neutrons and the rate of energy production will increase exponentially with time. In such a case the fissionable material is called SUPERCRITICAL. If on average less than one neutron from each fission is produced, then the fissionable material is called SUBCRITICAL for obvious reasons.

Two conditions must be met before fission can be used to create powerful explosions: 1) the number of neutrons lost to fission (from non-fission producing neutron captures, or escape from the fissionable mass) must be kept low, and 2) the speed with which the chain reaction proceeds must be very fast. A fission bomb is in a race with itself: to successfully fission most of the material in the bomb before it blows itself apart. The degree to which a bomb design succeeds in this race determines its efficiency. A poorly designed or malfunctioning bomb may "fizzle" and release only a tiny fraction of its potential energy.

[6] Steve Fetter, Valery A. Frolov, Marvin Miller, Robert Mozely, Oleg F. Prilutskii, Stanislav N. Rodionov, and Roald Z. Sagdeev, "Detecting Nuclear Warheads," Science and Global Security, Vol. 1, No. 3–4 (1990)

[7] Matter consists of various elements (e.g. air consists of oxygen, nitrogen etc.). Each element exists in nature in the form of atoms, which can be visualized as positively charged nuclei surrounded by negatively charged particles called electrons. Each nucleus consists of positively charged particles (protons) and neutral ones (neutrons). Nuclear radiation physics disregards the effects of orbiting electrons, as they don't play any significant role. The nucleus of an element can exist in nature in the

239 (93.5%), plutonium-240 (6.0%), plutonium-241 (0.44%), plutonium-242 (0.015%), plutonium-238 (0.005%). On the other hand the isotopic composition of WgU produced when virgin natural uranium is used as the feedstock for the enrichment process is: uranium-235 (93.5%), uranium-238 (5.5%), uranium-234 (1%). Such compositions are encountered in the fission primaries of nuclear weapons produced during the cold war.

Although the detailed design of nuclear weapons is classified, there is enough available information to obtain a rough idea of its geometry and its materials (type and quantities). Note that weapons geometry is the really classified aspect of a nuclear weapon as not only is it the most difficult part of its physics package but also it is a real deterrent to all potential terrorists. Its deterring effect originates from the fact that any violation of the right geometry will destroy the uniform spherical compression of the plutonium pit, which must be achieved in order to render the fissionable material supercritical[8]. On the other hand impurities in the fissionable material can initiate an early (or unwanted) chain reaction with disastrous results for the terrorist.

With regard to the fissionable material, WgU is used in the most primitive form of nuclear weapons based on a very basic physics package: the gun-type assembly[9], while WgPu is used in a more sophisticated design known as implosion assembly[10].

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form of isotopes that is nuclei with the same number of protons and different number of neutrons. Since the number of protons is the same for all isotopes (plutonium has 94) we just need to mention the total number of protons+neutrons (mass number) and the name of the element in order to identify the isotope. For example by plutonium-239 we are referring to element plutonium and in particular to the isotope which has 239-94=145 neutrons while by uranium-235 we are referring to the isotope of element uranium (92 protons) which has 143 neutrons. An element can have a large number of such isotopes some of which are radioactive that is they are transformed into other more stable elements thus reducing their initial mass. The time it takes for an isotope to reduce its mass by 50% is called half-life and ranges from fractions of a millisecond to billions of years. For example plutonium-239 isotope has a half-life of 24500 years while another of its isotopes plutonium-241 (with 146 neutrons) has a half-life of 14.4 years. The shorter the half-life the more radioactive the element and the faster it dies out.

[8] The principle issues that must solved to construct a fission weapon are: A) Keeping the fissionable material in a subcritical state before detonation, B) Bringing the fissionable material into a supercritical mass while keeping it free of neutrons, C) Introducing neutrons into the critical mass when it is at the optimum configuration (i.e. at maximum supercriticality)

[9] Assembling a critical mass by firing one piece of fissionable material at another is an obvious idea and was the first approach developed for designing atomic bombs. The two sub-critical pieces can be brought together by firing the cylindrical core down a gun barrel into the center of the hollowed-out pit. This is the design used in Little Boy, the bomb dropped on Hiroshima. The primary advantage of gun assembly is simplicity. It is as close to a foolproof design as ordinance technology allows. The drawbacks are: a) the lack of compression, which requires large amounts of fissionable material, and leads to low efficiency; b) only uranium-235 (and possibly U-233) can be used due to the slow insertion speed; c) the weight and length of the gun barrel makes the weapon heavy and fairly long.

[10] The key idea in implosion assembly is to compress a subcritical spherical, or sometimes cylindrical, fissionable mass by using specially designed high explosives. Implosion works by initiating the detonation of the explosives on their outer surface, so that the detonation wave moves inward. Careful design allows the creation of a smooth, symmetrical implosion shock wave. This shock wave is transmitted to the fissionable core and compresses it, raising the density to the point of supercriticality.

Implosion can be used to compress either solid cores of fissionable material, or hollow cores in which the fissionable material forms a shell. It is easy to see how implosion can increase the density of a hollow core - it simply collapses the cavity. This design was used in "the gadget" (the fist plutonium bomb tested in Alamogordo) as well as in Fat Man dropped on Nagasaki

The quantities involved are easy to estimate. The bare critical mass[11] of WgU is 50 kg[12] while the quantity used in Little Boy was 64.1 kg (enriched by 80%)[13]. On the other hand the bare critical mass of WgPu (delta phase[14]) is[15] 16 kg. In a crude nuclear bomb the most difficult part is of course to initiate a chain reaction at the right time and sustain it for as long as possible. In order to minimize the probability of zero yield a terrorist will naturally use a quantity of fissionable material as close to the critical mass as possible. Of course that entails the risk of predetonation but terrorists have already proved that the are willing to take such risks.

Thus, the most plausible range of quantities is: 10kg-16kg of WgPu, and: 50kg-100kg of WgU. The fact that the uncertainty in WgU is much larger than that of WgPu is due to the Gun-type assembly itself which allows the construction of a fool-proof crude nuclear device provided the masses of the two subcritical bullets of WgU (m1, m2) obey the relation: 25 kg<m1, m2<50 kg.

b) Boosted fission weapons

Soon after the design and testing of the first fission weapons it was realized that the extremely high temperature attained during a fission explosion can be used to initiate thermonuclear fusion of light nuclei[16]. In fact it is well known that the rate of thermonuclear energy production rate is an increasing function of density and temperature[17]. This fact led weapons designers to vent a small amount of deuterium[18] and/or tritium into the plutonium pit of an implosion assembly. The temperature attained during a fission explosion is larger than that existing in the center of the sun and thus it was enough to ignite the thermonuclear fusion of deuterium and/or tritium

[11] The bare critical mass is not the mass one would need to construct a device since by the use of a neutron reflector (tamper: a spherical metallic shell surrounding the fissionable material) the critical mass can be reduced by at least a factor of two.

[12] WgU sphere, 93.5% uranium-235, density=18.75 g/cc, unreflected, (source: H.Paxton, "Los Alamos critical mass data", LAMS-3067, UC46, 1964)

[13] R.Rhodes, "Trinity the making of the atomic bomb", Simon and Schuster Inc. ISBN 067144133 (1986).

[14] Plutonium metal can exist in six crystalline configurations. The two forms often mentioned with respect to nuclear weapons are a-phase and d-phase.

[15] WgPu sphere, 4.5% Pu-240, density=15.5 g/cc, unreflected. (source:H.Paxton, "Los Alamos critical mass data", LAMS-3067, UC46, 1964)

[16] Fusion boosting is a technique for increasing the efficiency of a small fission bomb by introducing a modest amount of deuterium-tritium mixture inside the fission core. As the fission chain reaction proceeds and the core temperature rises at some point the fusion reaction begins to occur at a significant rate. This reaction injects fusion neutrons into the core, causing the neutron population to rise faster than it would from fission alone.

[17] D.D.Clayton, Principles of Stellar Evolution and Nucleosynthesis, McGraw-Hill Book Company (1968)

[18] The hydrogen atom consists of a nucleus and an orbiting electron. There are various isotopes of hydrogen such as natural hydrogen which has only a proton in its nucleus, deuterium (one proton+one neutron) which exists in heavy water, tritium (one proton+2 neutrons).

just as it happens in the hydrogen-burning zone of ordinary stars[19]. The quantities needed to enhance (boost) the explosion are very small. For example the complete thermonuclear burning of a gram of deuterium can yield[20] an energy equivalent to 90 tons of TNT.

It is very unlikely that a terrorist will try to boost his/her weapon by using such elements. The purpose of an attack can very well be served by an ordinary fission weapon provided a nuclear chain reaction is achieved. As regards boosted fission weapons, if the terrorist does succeed in causing a nuclear explosion then the presence of the thermonuclear material will simply increase the explosive yield of the weapons. However, in case of a fizzle, although we should not be concerned about deuterium, as it is not radioactive, we should definitely investigate the lethal effect of the extremely radioactive tritium which will be present in the radioactive plume generated after the chemical explosion.

c) Fusion weapons (Hydrogen bombs)

Nowadays, it is practically impossible for a terrorist to design and build a crude nuclear hydrogen bomb. The knowledge required is profound and sophisticated. For example despite years of experience in nuclear weapons design, India and Pakistan still don't have the ability to build such a weapon. Nuclear history has taught us that on the road to nuclearization one has to follow the steps of the Oppenheimer group, which means that the most likely design of a crude nuclear device will be either a Gun-type assembly or an Implosion one. Furthermore, one can most plausibly assume that the terrorists will choose the material they can most easily steal or smuggle and these naturally are the most abundant WgU or WgPu. Note that over the past few decades the gun-type assembly[21] has been abandoned by the nuclear states since the implosion assembly[22] is more advantageous.

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[19] Fusion reactions, also called thermonuclear reactions, are reactions between the nuclei of certain isotopes of light elements. If the nuclei collide with sufficient energy (provided by heat in a bomb, or by a particle accelerator in the laboratory) then there is a significant chance that they will merge to form one or more new nuclei with the release of energy. Different nuclei combinations have different inherent probabilities of reacting in a collision at a particular temperature. The rates of all fusion reactions are affected by both temperature and density. The hotter and denser the fusion fuel, the faster the fusion "burn". See D.D.Clayton , ibid.

[20] "Controlled Thermonuclear Reaction" (1960), S.Glasstone and R.Lovberg. Prepared under the auspices of the OTI, USAEC. R.Krieger publishing Company, Malabar, Florida

[21] The primary advantage of gun assembly is simplicity and its foolproof design. The drawbacks are: a) the lack of compression, which requires large amounts of fissionable material, and leads to low efficiency; b) only uranium-235 (and possibly U-233) can be used c) the weight and length of the gun barrel makes the weapon heavy and fairly long.

[22] The primary advantages of implosion are: a) It allows materials with high spontaneous fission rates (i.e. plutonium) to be used; b) high density achieved, leading to a very efficient bomb, and allows bombs to be made with relatively small amounts of material; c) potential for light weight designs - in the best designs only several kilograms of explosive are needed to compress the core. The principal drawback is its complexity and the precision required to make it work. Implosion designs take extensive research and testing, and require high precision machining and electronics.

2) Meteorological conditions

a) Wind speed

Wind speed is the most decisive parameter of an attack with lethal agents. In fact if we assume that: 1) all other meteorological parameters are constant and 2) the radiological material has a relatively large half-life then the dose[23] received at a certain distance downwind from GZ is inversely proportional to wind speed while the area receiving a certain dose is also a rapidly decreasing function of speed. A low constant wind[24] speed is very favorable for another reason, namely the wind direction is predictable and can help the attacker control the plume in case of a fizzle. Large wind speeds will quickly disperse the material at large distances thus they are most likely to be avoided by the terrorists.

b) Stability category

Meteorologists distinguish several states[25] of the local atmosphere A, B, C, D, E, F. These states can be tabulated as a function of weather conditions, wind speed and time of day. According to the stability category the attack can result in a wide spectrum of lethal effects. Therefore the attacker will certainly take that into account, just as it happens by war-planners so that the lethal effects are maximized.
The relation of stability categories to weather conditions are depicted in the following table[26]

[23] Different types of ionizing radiation result in different biological damage. We measure this damage by using the physical measure of dose whose unit is the rem (or Sievert=100rem). In this study we will use the 50-Year Committed Effective Dose Equivalent (CEDE50) defined as the weighted average dose received by an individual in the next 50 years of his life due to remaining at the specified location throughout the entire radioactive material release (not throughout his life). Natural background radiation is approximately 0.3 rem per year (0.3 cSv). The current risk of dying from cancer (all types) for citizens of Europe and the USA is approximately 20 %. That means that on average one out of five of these citizens will die from cancer sooner or later regardless of being attacked with nuclear or radiological weapons. The current risk for associated radiation is 0.05 % per cSv (rem). Thus if you received a dose of 10 cSv (10 rem), to the whole body, your risk of dying from cancer would increase from 20 % to 20.5 %. For perspective a whole body CT delivers roughly a CEDE50 of 1 rem to the patient while a chest x-ray exam delivers a dose of 10-20 mrems (1mrem=1rem/1000).

[24] According to the Gaussian model for a particular stability category the concentration (and the dose) is inversely proportional to the wind speed. Hence, any wind speed higher than the one chosen will yield lower doses than the ones considered here at a particular distance.

[25] These categories, known as Pasquill categories, refer to how a parcel of air reacts when displaced adiabatically in the vertical direction

[26] F.A. Gifford "An outline of theories of diffusion in the lower layers of the atmosphere" in Meteorology and Atomic Energy 1968, D.H. Slade (Ed) US. Atomic Energy Commission, Washington DC.

Ground wind speed (m/s)	Strong Insolation[27]	Moderate insolation	Slight insolation[28]	Cloudy (100%) Day or night	Cloudy (>50%) night	Cloudy (<37%) Night
<2	A	A-B	B	D		
2-3	A-B	B	C	D	E	F
3-5	B	B-C	C	D	D	E
5-6	C	C-D	D	D	D	D
>6	C	D	D	D	D	D

In the Atlantic coastal site the probability of occurrence for the above stability categories is[29]:

A	B	C	D	E	F
4%	5%	2%	39%	32%	18%

c) Inversion layer

At first sight, it seems perfectly reasonable that temperature should decrease with altitude. However, due to various atmospheric phenomena there is sometimes an altitude at which the temperature gradient is inverted (temperature begins to increase with increasing altitude). The inversion layer acts as a blanket that limits the vertical mixing of the released radioactive material. Inversions can spread over large areas or be quite localized, and can last for many days or be of only a few hours duration. The region below the inversion layer is also referred to as the mixing layer. The mixing layer height ranges typically from 100 m to 3,000 m and can significantly increase or decrease air-concentration values and the respective lethal probabilities. Low altitude inversions occur usually at night (or early morning) due to radiation cooling of the ground[30]. As one can easily realize at night the population density in the streets will be very low.

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[27] Sun in sky higher than 60^0 above the horizon

[28] Sun in sky lower than 35^0 above the horizon (but higher than 15^0)

[29] S.Fetter, "The vulnerability of nuclear reactors to attack by nuclear weapons" Program in Science and Technology for International Security (MIT), Report #7 (1978)

[30] The vertical temperature profile is measured by launching a radiosonde (weather balloon), which consists of a balloon, a parachute, meteorological instruments, and a radio transmitter. As the balloon rises up in the atmosphere it transmits information about the temperature variation with height. Other less sophisticated methods exist such as using a thermometer to measure the temperature at two points: one near the ground and one at the roof of the heighest building in the area. If the temperature near the ground level is lower than the temperature at the roof then there is an inversion. A smoke generator is the cheapest and the most reliable method to simulate the attack before detonating the device. Smoke

Thus, it seems that nature somehow is against the terrorist who will have to choose between a) an attack during the day when many people will be in the streets but there is a high altitude inversion or no inversion at all and b) an attack in the small hours when the population in the streets is sparse but there is often a low altitude inversion. The most lethal choice will be during the early morning rush hour of a foggy day since the presence of fog (or smog in highly polluted areas) is an indication of a low altitude inversion which could motivate the terrorist to attack. This motivation will be enhanced by the fact that fog will increase confusion and make the visible detection of the actual plume difficult.

3) Radioactive plume details

a) Radiological material (quantity and nature of isotopes involved)

From the total quantity involved in the explosion only a fraction will be rendered airborne while the rest will be scattered around GZ. Moreover, from the airborne fraction only a small amount will have the right dimensions (small or large enough) to become respirable. Particles which are larger than 10μm will be captured in the upper respiratory track while others smaller than 1μm will be inhaled and exhaled without being retained in the organism. Experiments[31] have shown that when material such as WgPu are involved in a chemical explosion roughly 20% of the airborne mass is respirable. However, this is a rough number, which should not be taken for granted. Other unpredictable parameters can come into play, which force us to consider the 20%-scenario as the most favorable for the target.

The isotopic composition of the radioactive plume is crucial as the nuclear attack can involve WgU, or WgPu, or even tritium (see previous discussion). Thus we need to consider all possible scenaria and assemblies. Actually the air concentration as well as the dose received by an individual downwind is directly proportional to the source term (i.e. the quantity of the radioactive material). This is not the case, however, for isodose contours and the areas which are defined by them.

b) Deposition velocity

The heat and smoke of the explosion will lift small particles of plutonium up into the air and according to the nature of the released radioactive material these particles will settle to the ground as they are carried along by the wind contaminating the ground surface. Large particles will contaminate the immediate vicinity of the explosion while smaller (fine and mostly respirable) ones will travel large distances or will rise up at high altitudes until they are deposited on the ground. The velocity[32] at which this deposition takes place is called deposition velocity. Obviously, non-respirable material will have a much larger deposition velocity than respirable ones.

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will actually simulate the entire process and give evidence of the wind speed, wind direction, inversion etc. When no inversion is present an average lapse rate (known as adiabatic) is :–10 ^{0}C per km

[31] J.Dewart, B.Bowen, J.C.Elder (1982). LA-9445-PNTX-D (Los Alamos National Laboratory, LA, NM). (Operation Roller Coaster , Test “Double Tracks” ,Nevada Test Site)

[32] Particles and reactive gases in the plume are deposited on the ground surface (e.g. soil, leaves roofs etc.) by many physical mechanisms, such as impingement, mechanical trapping, electrostatic attraction and chemical reactions. The deposition velocity (in units of m/s, for example.) is empirically defined as the ratio of the observed deposition flux (in units of μCi / (m2-s), for example) and the observed air concentration near the ground surface (μCi / m3).

The deposition velocity is a parameter which needs careful examination. One cannot accurately know the distribution of such velocities for the entire respirable fraction so we need to consider worst- and best-case scenaria in order to bracket the lethal effects of the radioactive cloud. These two scenaria can be covered by assuming that the deposition velocity ranges from u_d=0.0 m/s (extremely fine aerosols) to u_d =1.0 m/s (relatively heavy and moist particles) although the value u_d =0.01 m/s is the most typical one[33].

c) Altitude of explosion (Height Of Burst: HOB)

It is very unlikely that the explosion will be tried above ground since the crude nuclear device will be similar in size and weight[34] to the "gadget" or the Fat-Man rendering any effort to elevate the device above ground very difficult. However, we cannot rule out the possibility that a helicopter will be used in a suicide attempt to achieve a high altitude detonation.

The effect of altitude is clear and predictable. Fizzles resulting from ground explosions yield higher doses than fizzles resulting from high altitude ones. The minimum HOB (in meters) which will not cause any appreciable fallout in the area around point zero is a function of the yield W (in kilotons) of the <u>fission</u> nuclear weapon and can be given roughly by the formula[35] $HOB=60W^{0.4}$. For example the Hiroshima bomb[36] was detonated at HOB=600m while its yield was W=15 kt. Since according to the given formula the HOB which would prevent any appreciable fallout is HOB=177 m we can see that the radioactive plume didn't cause much damage to Hiroshima, contrary to what most people believe nowadays. A crude nuclear device can produce much yields lower than 1kt and therefore any elevated detonation will not only reduce its blast and heat lethal effects but also the radioactive contamination resulting from it. It is now perfectly clear that a ground explosion is by far the most lethal choice of a terrorist and we will focus our study on it.

d) Explosive energy (Yield)

As we have already pointed out to implode a WgPu pit we need a multidimensional shock wave which is naturally caused by a spherical shell of HE[37]. On the other hand a gun-barrel assembly would use two bullets of WgU which would be fired at each other using again an appropriate quantity of chemical explosives. It is

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[33] G.A.Schmel, "Particle and Dry Gas Deposition: A Review ," Atmospheric Environment , Vol. 14 1980)

[34] Estimates and accounts of the size and weight of the gadget vary but it is obvious from all the publicly available pictures that it cannot possibly have been lighter than 500 kg while its effective diameter was roughly 2 meters

[35] S.Glasstone, ibid.

[36] S.Glasstone, ibid.

[37] Actually the design in the Fat man device included converging explosive lenses, but the actual design is of no importance to our study

well known that the WgPu pit in the gadget was roughly 10 kg while the explosives that suffice for its implosion don't need to be more than [38] 100 kg of HE.

It is very plausible, therefore, that the explosive energy of a total fizzle[39] regardless of its fissionable material will be approximately 10kg-100kg of HE. Note that if the chemical explosion manages to initiate a chain reaction fissioning a nominal quantity of the fissile material then we should expect an additional explosive energy of 17 kg TNT per milligram of fissioned material. If we take into account that the quantities of WgU or WgPu are of the order of kilograms one can realize that even a minimum nuclear yield will be a success for a crude nuclear device. Being consistent with our initial assumption of fizzles all our scenaria will be based on an explosive energy of 10kg-100kg TNT.

4) Timing

The time of attack is indeed a very decisive parameter, which needs special attention. During daytime many people will be in the streets and the radioactive plume will be easily mixed with other gases which form the usual urban pollution. The cloud will not be easily detected but this is not the case with the explosion itself[40]. Early detection can help since it may provide some warning to the public which can avoid inhalation of the cloud by finding shelter in nearby buildings or (staying indoors if are not caught in the streets). On the other hand, nighttime is not suitable for a terrorist attack against urban targets as most people will be indoors during the plume passage and the population density in the streets will be very small. Admittedly the attacker could escape much easier at night but as it has often been proved it is very easy to remotely detonate an explosive device in broad daylight without being arrested.

Moreover, as we have already pointed out, inversion occurs when low night temperatures follow high day temperatures reaching its peak early in the morning. This indicates that during the early morning rush hour the fizzle will be most likely met with an inversion, which would increase lethality. On the other hand the public will be particularly vulnerable during the rush-hour since most commuters will be either walking in the streets or using public means of transportation or in the driver's seat of their own cars blocked in some traffic jam.

Rain will definitely reduce casualties since it will actually wash down all radioactive particles and drive them down the sewers, therefore cloudy days, at first sight, won't be the terrorist's choice due to the possibility of rain. However, cloudy days are most likely to bring about a stable atmosphere[41] (e.g. Stability D) which is more lethal than the unstable one (Stability A) that we will choose as a starting point in our investigation.

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[38] Clifford Conn, "Synthesis of Energetic Materials", Energy and Technology Review, Jan-Feb, 1988. In this work there is shown that 100 kg of HE is more than enough to compress a sub-critical WgPu sphere to a highly super-critical state. As for the actual yield of the HE in the device it is common sense that even an inexperienced terrorist can explode successfully a quantity of HE

[39] No nuclear energy yield at all.

[40] For example the debris cloud generated by a chemical explosion of 22 kg TNT will reach a height of 165 meters.

[41] See section 2.b; D is a neutral atmosphere which means that a parcel of air is not as likely to rise up in the atmosphere as if it were in an unstable atmosphere (stability A)

5) Target conditions

a) Population density

It is common sense that the terrorists will choose a densely populated metropolitan area so that the lethal effects of their attack are maximized. Once we have estimated the lethal areas then we can simply multiply the population density by that area to estimate the number of casualties.
To create a realistic effect we will map out the lethal effects on a publicly available[42] satellite image of Washington DC. That way we will vividly depict the effects of such an attack helping all interesting bodies (Fire Brigade, National Guard, Police etc.) take in advance prevention and rescue measures.

b) Warning

Warning is an extremely effective countermeasure. If the public has early enough warning it can simply evacuate the area thus avoiding any exposure to the lethal effects of the attack. Even on a very short notice the public can simply have recourse to shelters or avoid being in the streets at the time of attack. If on the other hand, there is a fizzle then its immediate effects will be reduced by asking people to stay indoors. The radioactive plume will simply pass over the city and after some hours the air will be much safer than at the time of plume passage. As regards warning we will assume that the public is totally unaware of the attack thus adopting a worst-case scenario about passive defenses. Besides, in the recent attack against New York there was no warning at all thus maximizing the casualties of the attack.

Dosimetry, Lethality and Safety.

There are two forms of exposure to radiation during the radioactive plume passage:

Acute radiation exposure which occurs when a dose of radiation is delivered within seconds to 24 hours
Chronic radiation exposure which occurs when a dose is delivered within months to years.

Acute radiation exposure will be neglected in our study as neither WgPu nor WgU can deliver large doses within a very short time.

On the other hand chronic radiation exposure is the most important lethal factor after a fizzle since the fissile material of the device will be internalized and continue radiating the organism for a long time causing various forms of damage. We measure that damage by using the physical measure of dose whose unit is the rem (or Sievert=100rem). In this study we will use the 50-Year Committed Effective Dose Equivalent (CEDE50) defined as the weighted average dose received by an individual in the next 50 years of his life due to having remained at the specified location throughout the entire radioactive material release (not throughout his life).

Natural background radiation is approximately 0.3 rem per year (0.3 cSv). The current risk of dying from cancer (all types) for citizens of Europe and the USA is

[42] FAS

approximately 20%. That means that on average one out of five of US and European citizens will die from cancer sooner or later regardless of being attacked with nuclear or radiological weapons.

In the framework of the linear risk model the current cancer risk for associated radiation is[43] 0.05 % per rem (cSv). Thus if you received a dose of 10 rem (cSv), to the whole body, your risk of dying from cancer would increase by 0.5% (from 20 % to 20.5 %)[44]. This increase will be called in our study additional cancer risk 50 (ACR50). For perspective a whole body CT delivers roughly a CEDE50 of 1 rem to the patient while a chest x-ray exam delivers a dose of 10-20 mrems[45].

According to the linear risk model, which is the most conservative one, one cancer death will ensue regardless of whether a total dose of 2000 rem is delivered to a single individual or a single dose of 1 rem to a total of 2000 individuals. Thus the cancer risk coefficient CRC50 is:

CRC50 = 1 Cancer / 2000 person-rem

In the United States, workers are limited to a whole-body dose of 5 rem per year which, amounts to a CEDE50 of 250 rem (ACR50=12.5%). It is very natural, therefore, to regard the distance from GZ at which an individual receives a CEDE50 of 100 (10) rem as a reasonably critical (safe) distance since it causes to an individual standing there an ACR50 of 5% (0.5%).

In order to investigate the effects of all previous parameters on the lethality of the attack we need to approximate the most probable values of such an event. After we have achieved a first approximation we can vary all parameters within their reasonable limits in order to derive a worst- and a best-case scenario.

Worst Case Scenario A (The Fat Man)

It is better to build the worst case scenario while studying quantitatively the effects of all parameters involved in the attack. Some of them are obvious and we will take them for granted while others need further elaboration and clarification.

Nuclear terrorists have built (or obtained in the black market) a crude nuclear device based on implosion assembly (Fat Man). They have chosen the most favorable spatial, temporal and meteorological conditions which would maximize the lethal effects in case of a fizzle. To a first approximation according to all the previous data those conditions are[46]: **a sunny day with a light breeze that makes leaves rustle and is felt on face[47], most likely during the morning rush-hour. The ground zero**

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[43] International Commission on Radiological Protection , "Limits for Intakes of Radionuclides by Workers", ICRP Publication 30 (Oxford: Pergamon Press, 1990)

[44] Similarly, a dose of 100 rem would increase the risk by 5% while a dose of 300 rem by 15%.

[45] 1mrem=1rem/1000

[46] Similar are the most favorable conditions for a radiological attack.

[47] Minimum wind speed <2 m/s, Stability category A. The actual wind speed can be empirically determined by observing the smoke from a chimney near ground zero. Vertical downwind drifting of the smoke starts at wind speeds>0.5 m/s while at lower speeds smoke rises vertically. Of course the

will most probably be close to where the population density is maximum for obvious reasons[48]. Moreover, we assume that the attacker has naturally obtained information about the time at which the inversion layer height is usually at a minimum[49] above the target. We also assume that the most plausible target is a large densely populated US metropolitan city, which has not been warned about the attack.

The attacker detonates (at ground level) a crude nuclear warhead, which contains a barely subcritical plutonium core (15 kg of WgPu). The detonation fails to produce any nuclear yield and the result is a radiological explosion (fizzle). The chemical explosives, which were unsuccessfully used to initiate a chain reaction, yield an energy, which ranges from 10 to 100 kg of TNT. Alternatively, we may assume that a similar quantity of stolen WgPu is assembled as a radiological weapon and the assembly is exploded using the same quantity of HE.

Naturally, there is always the chance that the terrorist would be in possession of a fully assembled modern warhead, which could weigh 45-200 kg and have the size of an ordinary 8-inch artillery shell (of the order of 8 cm)[50]. In such a case the fissile quantities involved are less than considered here, which renders the present scenario the most conservative one (as far as quantity is concerned).

In figure 1 we plot the centerline CEDE50 as a function of distance. As we see there is a non-zero probability[51] that an individual standing 100 km away from GZ will receive a dose of 10 rem (ACR50=0.5%). Similarly, a person standing at a distance of 4 km can receive doses larger than 100 rem (ACR50=5%).

FIGURE 1

In figure 2 we map the dose distribution over the city. The middle (inner) contour defines the area which will receive doses larger than 100 (300) rem. All people inside the middle (inner) contour will run an ACR50 of more than 5% (15%). In figure 3 we magnify the dose contours close to GZ and we see that the area which will receive doses larger than 1000 (500) rem will be 0.007 sq.km (0.091 sq.km) while the people inside it will be subjected to an ACR50 larger than 50% (25%).

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direction of drifting can reveal the direction of the wind which will eventually help terrorists aim their lethal agent better.

[48] Actually an attack at the outskirts of the city with the wind blowing towards the city would maximize casualties. However such an attack runs the risk of the plume being blown away from the target if the wind changes direction. Since a typical large city usually occupies an area smaller than 250 square kilometers we will study all our scenaria on a map whose dimension are of a similar order of magnitude (100 sq.km)

[49] There are some areas where the creation of inversion is very predictable such as those near mountains where the deflection of a warm wind by the mountains over cooler air on the lee side of the mountain is the perfect generator of an inversion layer. The existence of inversion can be empirically detected as follows: If close to GZ there is a chimney (e.g. from a factory) then if its smoke instead of rising vertically is bent abruptly at a certain height above the chimney then that is roughly the mixing height while the direction of the wind is also obtained by the same method.

[50] T.B.Cochran, W.M.Arkin, M.M.Hoening., Nuclear weapons data book ,Volume #1 (Cambridge Massachusetts :Ballinger, 1984)

[51] In fact that probability becomes certainty if the wind blows directly towards an individual who never leaves his/her position throughout the entire plume passage. At the wind speed we have considered the plume will reach that person in roughly 27 hours. By that time, all the parameters of the attack will have changed including the position of the person.

Note that the area covered with doses larger than 1000 rem is so close to GZ that people inside that area may also suffer from other injuries caused by the chemical explosion.

FIGURE 2

FIGURE 3

If we know the population density of the area defined by an isodose contour then the minimum number of additional cancer deaths 50 (ACD50) [52] inside that contour can be estimated from the following simple rule:

ACD50=CEDE50 X CRC50 X Population Density X Area

Table 1. The minimum number of ACD50s caused by inhalation during the passage of a plume generated by the attack described in Scenario A for various average population densities encountered in Washington DC[53]

	1,000 p/sq.km	*10,000 p/sq.km*	*100,000 p/sq.km*
Figure 2 (middle contour)	145 (2,900)	1,450 (29,000)	14,500 (290,000)
Figure 2 (inner contour)	43.5 (290)	435 (2,900)	4,350 (29,000)
Figure 3 (middle contour)	22.7 (91)	227 (910)	2,270 (9,100)
Figure 3 (inner contour)	3.5 (7)	35 (70)	350 (750)

The data in Table 1 should be read column by column as follows:

<u>First column</u>
If the population density of the city is 1,000 people/sq.km then inside the middle (inner) contour of Figure 2 there are 2,900 (290) people receiving doses larger than 100 (300) rem. The total man-dose inside the middle (inner) contour will be larger than 290,000 (87,000) man-rem and the ACD50s will be at least 145 (43.5). Therefore the individual dose inside the middle contour and outside the inner one (2.61 sq.km with 2,610 people) should be 100 rem<D<300 rem while the ACD50s in this area would be 130.5<ACDs<391.5

Using the information of Figure 3 we see that inside its middle (inner) contour there will be 91 (7) people who will receive doses larger than 500 (1000) rems and the ACD50s will be at least 22.7 (3.5). Accordingly, in the area defined by those two isodose contours of figure 3 (0.084 sq.km, 84 people) the doses will be 500 rem <D<1000 rem while we expect 21<ACD50s< 42.

[52] Additional deaths that will ensue in the following 50 years after the attack.

[53] Or any other large metropolitan city, of course.

Moreover in the area defined by the 1000 rem isodose contour and the 100 rem one (2.9 sq.km, 2,893 people) the doses will be 100 rem<D< 1000 rem and of course there will be roughly 145<ACD50s<1450.

In the interpretation of columns 2 and 3 of Table 1 all previously mentioned ACD50s should be multiplied by 10 and 100, respectively.

We can now investigate the effects of the parameters of the attack.

Effects of deposition velocity

First let us assume that the deposition velocity is larger than zero (assumed originally) i.e. u_d=5 cm/s which is a reasonable upper limit for dry atmospheres.
If all other parameters are kept constant then for average distances we derive figures 4-5.

FIGURE 4

FIGURE 5

As we expected larger deposition velocities will shrink the isodose contours since the material will be depleted faster[54]. Note for example in figure 4 that if the deposition velocity is u_d=5 cm/s the area covered with doses larger than 100 (300) rem is now 1.3 (0.19) sq.km i.e. 55(35)% less than in the zero-deposition-velocity scenario while the minimum ACD50s will follow the same reduction pattern for all the population densities[55].

Similarly in figure 5 one can observe the same trend in isodose contours and ACD50s. Now the area defined by the isodose contours 100 (500) rem and 300 (1000) rem is 1.11 (0.063) sq.km and the ACDs will be subject to the constraint 55.5<ACDs<166.5 (15.75<ACDs<31.5)

This proves the importance of the deposition velocity to the lethality of the fizzle. The finer the plume the smaller the deposition velocity which can greatly enhance the lethal effect of the attack.

Effects of wind speed

Now let us assume that in Scenario A the wind speed is[56] 4 m/s, that is four times larger than the one considered in the previous scenaria, which is a plausible assumption too[57].

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[54] This in turn will increase ground concentration but this is immaterial to our study since in an urban area decontamination is much easier than in rural areas.

[55] Had we used the wedge model to estimate the effects of deposition velocities at such short distances from GZ we would have come up with the unrealistic result that a reduction of the deposition velocity by an order of magnitude causes a similar increase to the associated lethality. This proves that the wedge model is inappropriate for our study.

[56] If all other parameters are kept constant then this will also affect the stability category which for a wind speed of 4 m/s will be B. However, we will continue using stability category A in order to isolate the effect of wind speed.

In figure 6 we plot the centerline CEDE50 as a function of distance. As we see the distance from GZ beyond which a person cannot possible receive a dose of 10 rem (0.5% ACR50) is 20 km while when the wind was 1 m/s the respective distance was 100 km.

FIGURE 6
FIGURE 7

In figure 7 we can observe that the area covered with doses larger than 100 (300) rem has shrunk[58] to 0.21 sq.km (0.005 sq.km) that is roughly 14 (58) times compared to the respective areas covered with (at least) the same doses when the wind blows at 1 m/s. Since the minimum ACD50s that will ensue inside an isodose contour scales with the area we see that lethality is a rapidly decreasing function of wind speed[59].

Effects of mixing height

Let us assume that in Scenario A the mixing height is 1000 m. Then we derive figure 8 where we see that the isodose contours now define much smaller areas. Namely, the area covered with doses larger than 100 (300) rem is now 0.31 sq.km (0.074 sq.km) that is roughly 9 (4) times smaller than the respective areas covered with (at least) the same doses when the mixing height is 100 m. If we further increase the mixing height it will have no practical effect on the isodose contour due to the relatively small height of the cloud top (roughly 165 m)[60]. If we follow the usual scaling rule and assume a population density of 1000 p/sq.km then in the area defined by the middle (100 rem) and inner (300 rem) contours (i.e. 0.236 sq.km) there will be 236 people and the ACD50s will now be: 11.8<ACD50s<35.4.

FIGURE 8

Likewise, in the area defined by the outer (10 rem) and inner (300 rem) contours (i.e. 3.826 sq.km) there will be 3826 people and the ACD50s will now be: 19.14<ACD50s<574.

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[57] In fact the wind is neither expected to blow towards the same direction all the time, nor is it expected to blow at a constant speed. However, we can bracket the wind speed effect by varying it under the assumption that it is kept constant throughout the plume passage.

[58] For the curious mind we should underline that the radioactive material doesnt disappear because of the strong wind. Simply stronger winds blow the cloud further and thus they reduce its air concentration. The plume will now reach further distances than when driven by a weak wind but with relatively lower concentrations.

[59] An infinitely large wind speed would practically mean that plume deposition would take place at an infinitely slow rate (similar to a zero deposition velocity) and that the plume would reach infinite distances with infinitely small concentrations. Note that if the population density is the same to infinity the entire plume will finally be inhaled and the total number of ACD50s would be the same regardless of the wind-speed.

[60] That means that the cloud never reaches the ceiling (mixing height).

Effects of Height Of Burst (HOB)

As we have already mentioned the terrorist may finally decide to detonate the crude nuclear (or radiological) weapon at a certain altitude above ground. Actually the HOB will play a decisive role in the partition of the destructive effects of the nuclear explosion namely: thermal, nuclear and blast ones. However, if the mixing height is smaller than the HOB then the plume cannot reach the ground and will therefore spread out horizontally producing what is called fanning (or lofting if the plume tends to diffuse upwards).

Moreover, as we have already explained (see Section 3c) for very small yields, such as the one expected from a crude device, a ground explosion will be the safest option for a terrorist and therefore we will confine our study to ground explosion scenaria

Effects of explosive energy yield

In all above sub-scenaria we assumed that the device was unsuccessfully detonated using 10 kg of TNT. Let us know assume that the explosive energy is an order of magnitude larger. Then according to Figure 9 the area covered with doses larger than 100 (300) rem is now 2.7 sq.km (0.26 sq.km) that is roughly 7% (10%) smaller than the respective areas covered with (at least) the same doses when the explosive energy is 10 kg of TNT. Lethality (i.e. ACD50s) scales with the areas of the above isodose contours as usual.

If instead we use only 0.5 kg of TNT then lethality increases by 13% (10%) as figure 10 indicates. It is now obvious that the smaller the yield the larger the lethality. Therefore the terrorist who is interested in maximizing lethality during a radiological attack will not use liberal quantities of HE, as this would have the opposite effect in case of a fizzle.

FIGURE 9

FIGURE 10

Effects of boosting (Tritium release)

We now assume that the terrorist has used a small quantity of Tritium and/or Deuterium in order to boost the nuclear device[61]. Deuterium is not radioactive but Tritium is roughly 10000 times more radioactive than WgPu and demands special attention. A typical quantity needed to boost the weapon is a few grams of Tritium and that is what we assume to be explosively released along with the WgPu during a fizzle.

FIGURE 11

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[61] It is common knowledge, nowadays, that boosting doesn't occur at the naïve way we have described here, that is neither tritium nor deuterium is used in pure isotopic forms. Tritium is much too expensive to produce and it decays so fast that it needs to be replenished all the time (12.3 years half-life). Deuterium, on the other hand, bearing all the chemical properties of hydrogen, is difficult to store. It must either be highly compressed or liquified at extremely low temperatures. Weapons designers use lithium deuteride a chemical compound which is a stable solid. Fast neutrons from plutonium fission are captured by lithium and produce tritium, which in turn reacts with deuterium. However, as an extreme action a terrorist may use pure tritium or deuterium in the core of the plutonium pit aiming at both boosting and contaminating the area around GZ in case of a fizzle. Since deuterium is not radioactive we need not investigate the lethal effects of its explosive release.

Figure 11 shows that a few grams of Tritium cannot have any significant lethal effect. Note for example that at distances larger than 100 m from GZ no one will receive doses larger than 0.010 rem (roughly equal to the dose delivered by a chest x-ray). Even people as close to GZ as a few meters will not receive any significant dose. Similarly negligible are the results if we increase the amount of tritium tenfold.

Therefore the lethal effect of the boosting material is insignificant compared to that of WgPu. The distance at which one might receive some non-negligible dose is closer than the distance at which a person would be severely injured by the explosion.

Effects of Stability Category

In our worst case scenario we have chosen stability category A since that combines low wind speeds and sunny days. As a first approximation we assumed that the attacker would choose a clear day for fear of rain which would wash out the plume and decrease lethality. However, cloudy mornings are more likely to be accompanied by inversions than sunny ones. Moreover, stability A is the most unstable one characterized by turbulence and thermal air currents, which render the course of the plume very uncertain.

Stability F, on the other hand, is the most stable one and is usually accompanied by inversion. Since the terrorist will strive to combine stability and low wind step we are forced to consider the most stable category that combines these features that is stability category D (see relevant table in section 2b). This scenario produces figure 12 which shows that the area covered with doses larger than 100 (300) rem is now 5.5 sq.km (0.17 sq.km) that is roughly 100% larger (40% smaller) than the respective areas covered with (at least) the same doses under stability category A.

FIGURE 12

Note that we have also assumed that the attack takes place under other stability categories. We have found that the uncertainty induced by the stability parameter is such that the ACD50s might be three times as many (e.g. stability category D)[62] as estimated under stability A. Therefore the stability category of our initial scenario (i.e. A) is the most conservative for the attacker[63] and the reader should bear in mind that in a worst case scenario lethality might actually be three times as high as depicted in Scenario A.

Ground Contamination

During the plume passage, radioactive dust particles will settle on the ground contaminating it. Naturally the terrorist will be mainly interested in the immediate effects caused by the plume passage, as he knows that the ground radiological contamination that will ensue will be far less lethal. Consequently we will estimate[64]

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[62] That means an 100%-cloudy day

[63] We use the term conservative always in conjunction with the attacker or the target. The scenario which is the most conservative (pessimistic or worst case) for the attacker is simultaneously the most optimistic (best case) for the target.

[64] We need to give some facts about plutonium here, which will be very useful in setting safety guidelines. We measure radioactivity in Curies (Ci). To indicate the quantity of Curies per gram of a radiological material we use the notion of the specific activity. The specific activity of plutonium-239

the ground contamination after a fizzle assuming conditions that maximize the lethality of the plume passage[65].

FIGURE 13

Figure 13 shows that after the attack an area of (8.7/13/23) sq.km will be left contaminated with a WgPu ground density of (10/5/1) μCi per square meter.

FIGURE 14

Similarly figure 14 shows that after the attack all areas (ground surfaces) within a radius of 1 (10) km from GZ can possibly be contaminated with densities higher than (500) 1 μCi/m2. Therefore, if indeed such an attack takes place all areas within a radius of 10 km should be evacuated until radiation detection and cleanup operations ascertain their safety. Even if we increased the maximum permissible density to 100 μCi/m2 that would still mean that all areas within a radius of 5 km from GZ will have to be evacuated.

The evacuation period would last for days or weeks with consequences that can be easily imagined[66]. However, no citizen is expected to believe that their area is safe when tens of thousands of people are evacuating the high-risk zone. Consequently, the entire city will soon be deserted until the authorities announce that there is no radiation risk any more.

Worst Case Scenario B (The Little-Boy)

All the previous arguments apply to the WgU crude nuclear devices as well. Instead of a source term of 15 kg WgPu our scenario should now involve roughly the amount of WgU used in the Little Boy assembly that is 65 kg WgU. However, before we investigate such a realistic scenario it would be very enlightening to compare the

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is 0.062 Ci/g, which means that each milligram of plutonium "carries" 62×10^{-6} Curies or else 62 microCuries (μCi). The total cancer risk from plutonium inhalation is at most 10 ACDs per mg inhaled (see Fetter and Von Hippel, ibid.) which can be interpreted as (roughly) 0.16 ACD50s per μCi inhaled. Now assume that we have a uniform surface density of WgPu after the attack equal to D $\mu Ci/m^2$ and that all this quantity is resuspended and confined within a height of 2 meters (worst case scenario). The air concentration will be (D/2) $\mu Ci/m^3$ while if we further assume a normal breathing rate of 3.33×10^{-4} m^3/s then an individual will inhale 0.6D μCi per hour or else 0.01D mg of plutonium per hour. This means an approximate ACR50 of (at most) 10D % per hour of inhalation. Taking into account that: a) other less conservative scenaria estimate 3 ACD50s per mg of WgPu, b) a resuspension plume cannot really be so confined nor can it be continuous c) the ground density will be depleted due to various natural processes. We can adopt the following risk guidelines for WgPu: A ground deposition density of D μCi/m2 entails an ACR50 of D% per hour of inhalation. This means that a density of 1 μCi per m^2 could expose an individual to an ACR50 of 1% per hour of inhalation. We will adopt this density as a fair limit for all areas that should be evacuated. Note that according to the EPA guidelines Sr-90 density of 2 μCi/m2 renders agricultural land unusable (see "Arsenal" by Kosta Tsipis, ibid.).

[65] Wind speed 1m/s, stability category D, mixing height 100 m.

[66] Evacuation procedures and their effects are very usually shown on TV regarding third world countries where large numbers of people are displaced for fear of being attacked. The most recent large-scale evacuation procedure took place in (former) USSR after the Chernobyl accident where the financial, social and psychological havoc was of extraordinary proportions.

lethal effects per unit mass delivered by WgU and WgPu as they may both be used as radiological weapons.

To that end we have produced figure 15 under the same conditions as figure 2 only now the fissile material is WgU. Note that the effects are dramatically less lethal. While in the case of WgPu (figure 2) all people inside an area of 0.25 sq.km would receive doses larger than 300 rems (15% ACD50s) when WgU is released under similar conditions (figure 12) in the same area the doses will be roughly 3000 times smaller and so will lethality[67].

FIGURE 15

In view of the above we will not investigate the Little Boy fizzle any further while the reader should keep in mind that its effects are roughly one thousand times less lethal than Fat man ones.

In order to create a realistic effect we will apply our risk assessment study to a specific metropolitan US city which needs special attention since it is certainly a potential target[68] of a terrorist attack, i.e: Washington DC.

Map 1,2 are satellite pictures[69] of Washington DC. On map 1 we have considered three different GZs and have plotted the areas defined by the 300-rem isodose contours (worst-case scenario A)[70]. The reader might regard the gray transparent areas as the ground level cross section of a cloud which will deliver doses larger than 300 rems to anybody who is inside it (at ground level). All people who will find themselves inside that cloud will run an ACR50 of at least 15%. Likewise, Map 2 shows[71] the area covered with doses larger than 100 rem so that all people who will be immersed in that cloud will run an ACR50 of at least 5%.

Map 3, on the other hand, shows the areas close to the White House which would be covered with densities larger than 1000 μCi/m2 and should be evacuated immediately after the explosion. Actually all the area shown on the entire map should be evacuated as it runs a non-negligible risk of being contaminated with surface densities larger than the maximum permissible one.

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[67] The effect of U238 and U234 isotopes will only vary that estimation by a factor of 2-3

[68] Fundamentalists, who are the most likely to attempt a nuclear attack against USA, are known to select targets which represent the American power and authority so that by destroying them they can convey a message to the public. The US capital is the city, which, if attacked successfully, would satisfy the ego of a terrorist.

[69] FAS

[70] Note the arrow pointing to the White House (its yard is also denoted by a dark rectangle on Map 2).

[71] Only one GZ is considered here

Comments and conclusions.

We have now investigated all the parameters which are going to play a crucial role during a fizzle. The conclusions can be summarized as follows:

I) The Little Boy fizzle has been found to be roughly a thousand times less lethal than a Fat Man one and should not be considered a major threat to the target.

II) The most lethal time of attack is a cloudy (or foggy) morning of a working day with a light breeze that makes leaves rustle and is felt on face[72], most likely during the early morning rush-hour

III) The population density of the target is function of time therefore the attacker will try to choose the time that maximizes it. However, that time is not always accompanied by the most favorable meteorological conditions for an attack. For example while nights cause inversions more often than days, the population is much less exposed at nights than at days.

IV) The wind speed compared to the inversion layer is more important to the lethality of the fizzle. Thus, low wind speeds will be the most decisive meteorological factor.

V) The number of casualties cannot be measured shortly after the attack. It will take long-term monitoring of all individuals exposed to the radioactive plume to obtain the actual lethality of the fizzle. Therefore in all radiological attacks the term casualties should be replaced by the term Additional Cancer Deaths (ACD50s) within 50 years after the attack.

VI) In a large metropolitan city like Washington the number of ACD50s due to a typical fizzle can range from hundreds to tens of thousands according to the population density and the parameter of the attack described in the text. However, in such a city, during a 50-year period after the attack there would be hundreds of thousands of cancer deaths (CD50) due to reasons other than the attack. Therefore, the actual long-term effects of the attack can easily pass undetected[73] since they may be overwhelmed by the usual cancer mortality.

VII) After a fizzle more than 10 sq.km of the attacked metropolitan city will have to be evacuated, while even places considered secure will definitely be evacuated spontaneously by their inhabitants. All areas within a radius of 5 km will run a non negligible risk of being contaminated with non-permissible surface densities.

VIII) The White House apparently has no natural barrier which might prevent a lethal plume from reaching it. Since it is the most probable target in the world security measures should be taken so that, the most natural means of delivery of a lethal agent (i.e. the air) would not easily contaminate the premises. Its location is by far the most vulnerable one as it gives "a clear shot" from every

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[72] Wind speed <3 m/s, Stability category D. The actual wind speed can be empirically determined by observing the smoke from a chimney near ground zero. Vertical downwind drifting of the smoke starts at wind speeds>0.5 m/s while at lower speeds smoke rises vertically. Of course the direction of drifting can reveal the direction of the wind which will eventually help terrorists aim their lethal agent better.

[73] For example according to the 2000 census the population of Washington DC is 5,894,000 people of whom at least 736,000 are expected to die of cancer in the next 50 years (20% cancer mortality in an 80-year life span). If a fizzle causes the enormous amount of 10,000 ACD50s then that would be recorded as an 1.3% statistical fluctuation.

angle. Admittedly, current security measures may indeed prevent a sniper from assassinating a resident of the White House. However, as we have proved in the present study, the ubiquitous means of delivery of a lethal agent can always find its way to the target by simply overcoming its entire vicinity.

MAP 1

MAP 2

MAP 3

MAP 4